10 Comparative Analysis of UV-B Exposure Between Nimbus 7/TOMS Satellite Estimates and Ground-Based Measurements

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Abstract This study describes the patterns of variation in ultraviolet (UV) exposure across time and space, using two continental scale datasets on UV radiation, and conducts a comparative analysis of two sources of noontime UV-B exposure data across the continental U.S. One dataset was collected from 37 ground-based stations equipped with broadband UV-B-1 Pyranometers across North America whereas the other dataset was of synchronous satellite data collected from the Nimbus-7/TOMS sensor. Comparisons of these datasets confirmed agreement between the ground-based measurements and the TOMS satellite estimates with correlation coefficients of 0.87 and 0.95 for daily and monthly Ultraviolet Index (UV-I) time series (i.e., a common metric of UV radiation exposure), respectively. The UV-I value observed by the TOMS sensor is generally greater than that of the USDA ground-based measurements, and the relative error of daily change is, on average, between 5% and 12%. With these two datasets from 1999 to 2005, the trend analyses for daily and monthly UV-I change are statistically summarized at four representative stations distributed across the western U.S as an integral part of the USDA monitoring network. Spatial and temporal features may then be illuminated and retrieved according to UV-I distribution. Overall, the UV-I data acquired by the TOMS sensor can sufficiently detect the effect of spatial variation in topography, whereas continuous measurements through the USDA UV-B

ground-based monitoring network can provide better temporal resolution on holistic changes in UV-I within the last few years.

Keywords UV-B, UV-I, remote sensing, TOMS, U.S.

10.1 Introduction

The sun gives off ultraviolet (UV) radiation that may be divided into three categories based on the wavelength: ultraviolet-A (UV-A, from 320 nm to 400 nm), ultraviolet-B (UV-B, from 290 nm to 320 nm), and ultraviolet-C (UV-C, from 100 nm to 290 nm). It is known that sunlight can impact the skin, causing premature skin aging, skin cancer, and a host of skin changes (Dharmarajan, 2008). Exposure to UV light, such as UV-A or UV-B, from sunlight accounts for 90% of the symptoms of premature skin aging (Dharmarajan, 2008). Ultraviolet light, UV-B in particular, also has the potential to harmfully impact vegetation and livestock. This is especially true at lower latitudes (30.8°S – 30.8°N) during the summer, where the amount of noontime UV radiation is the largest because of smaller solar zenith angles (SZAs). Due to the negative effects of ultraviolet light on humans, livestock, agricultural crops, and forest health, it is critical to be able to assess levels of UV radiation and to estimate its impacts. Many factors affect UV radiation levels and measurements, including extraterrestrial solar irradiance, atmospheric ozone, cloud reflectivity, aerosol amounts, and ground albedo. For example, changes in the earth's atmospheric condition caused by anthropogenic and natural pollutants has led to the well-documented decline in ozone and the corresponding increase in UV irradiance at the earth's surface. Yet the amount of ultraviolet radiation penetrating to the earth's surface with wavelengths shorter than 320 nm (UV-B) can be reduced by tropospheric ozone absorption, aerosols, clouds, and Rayleigh scattering in the atmosphere.

Concerns about increases in surface UV-B have triggered immense scientific and societal interest, especially following the discovery of the ozone hole in the Antarctic and the serious ozone decreases in middle and high latitudes (Herman et al., 2000; 2001; Krotkov et al., 2001). To date, UV has been observed from space for more than 20 years. Early satellite UV measurements were made by the Backscatter Ultraviolet (BUV) sensor onboard the Nimbus 4 platform, which was launched in 1970 and continued functioning for several years. Nimbus 7 provided the longest high-quality space-borne UV observation with the aid of the total ozone mapping spectrometer (Nimbus-7/TOMS) from 1979 – 1993. The National Oceanographic and Atmospheric Administration (NOAA) weather satellites also measured UV radiances for a considerable period with the Solar Backscatter Ultraviolet (SBUV) sensor. TOMS was mainly designed for determining the vertically integrated ozone amount, while SBUV was designed for obtaining ozone profiles. These data are invaluable for studying both ozone and surface UV radiation. In addition to the Nimbus7, the TOMS instrument was also flown onboard the Russian Meteor 3 from 1991 to 1994, on the Japanese ADEOS for less than a year in 1996 – 1997, and is currently on the National Aeronautical and Space Administration's (NASA) Earth Probe. Ozone data may also be derived from the TIROS Operational Vertical Sounder (TOVS), the Stratospheric Aerosol and Gas Experiment (SAGE and SAGE Ⅱ), the Global Ozone Monitoring Experiment (GOME) onboard the European ERS-2 satellite, among others. Together, these satellites provide a wealth of data regarding ozone and UV radiation (Wang et al., 2000; Fioletov et al., 2001; 2002; 2003; 2004).

In addition, hundreds of ozone/UV ground-based stations are operating around the globe. Such a long-term, well-established ground-based monitoring network, equipped with the SUV-100 double monochromator instrument, produces consistent UV-B measurements which may be used as the ground-truthing data for satellite data assimilation. These data are well archived by the World Ozone and Ultraviolet Radiation Data Center (WOURDC) of the World Meteorological Organization (WMO) operated by Environment Canada. Stations in the U.S. include the National Science Foundation (NSF) Polar UV Network and the U.S. Department of Agriculture (USDA) UV-B Monitoring and Research Program (UVMRP), which was initiated in 1992 to provide information on the geographical distribution and temporal trends of UV-B radiation in the U.S. The initial network of 12 stations was established in 1994. The network has expanded to 37 climatologic locations plus several research sites. Comparisons of UV-B estimates between Nimbus 7/TOMS satellite data and ground-based measurements may contribute to the potential spatial application of satellite images in the future.

Previous efforts for comparing these two time series laid down the basic foundation of the potential accuracy of the TOMS imageries (Vitali et al., 2002; Ye et al., 2002; Ziemke et al., 2003). Near-to-real time, as well as "archive quality," Brewer UV observations, which are performed with well-maintained and calibrated instruments over the Northern Hemisphere, have been used for the validation of the TOMS imageries. Kaurola (2000) studied the correspondence between the data from: (1) ground-based observations, (2) surface UV Index (UV-I) (i.e., a common metric of UV radiation exposure) determined using TOMS satellite measurements, and (3) reconstructed UV doses using observations of global radiation. Different trend estimates were in very close agreement with each other. Kalliskota (2000) adopted daily UV erythemal doses estimated from Nimbus-7/ TOMS measurements (from 1991 to May 1993) and those calculated from ground-based spectroradiometer data at Ushuaia, Argentina (for 573 days), Palmer, Antarctica (for 450 days), and San Diego, California (for 149 days), and then made comparisons between the datasets. McKenzie (2001) studied the differences between satellite-derived estimates of UV and ground-based measurements at three stations located in northern Europe (Belsk, Norrköping, and Jokioinen) and a clean air site in the Southern Hemisphere. Vitali (2002) found that there are some systematic differences between the measurements of the ground and satellite-retrieved UV irradiance. The Brewer data are lower than TOMS-estimated UV irradiance by 9% to 10%, on average. Cede (2004) obtained data over a period of more than 4,700 days from 1997 to 1999 at 8 stations of the Argentina UV Monitoring Network to study the major factors that are causing the differences between satellite-derived and ground-based UV erythemal irradiances and doses. Using hourly UV-I values at 45 sites in Canada, Fioletov (2003) made direct comparisons of Brewer measurements and TOMS data showing an agreement within 2% to 3%, except during periods of melting snow when variations in snow albedo yielded higher errors in the UV irradiance derived from both sources. Using long-term monthly mean UV-I values for Canada and the U.S. Fioletov et al. (2004) found that in summer, TOMS UV-I climatology values are 10% to 30% higher than those derived from global solar radiation and other parameters. In this instance, TOMS estimates agree with Brewer measurements. The difference is probably related to aerosol absorption and pollution effects in the lower troposphere which are not currently detected from space. For 21 of 28 mid-latitude Brewer sites, long-term mean summer UV measured values and UV derived from global solar radiation and other parameters agree to within +5% to +7% (Fioletov et al., 2004). The remaining 7 sites are located in "clean" environments where TOMS estimates agree with Brewer measurements, while UV derived from global solar radiation and other parameters is 10% to 13% lower (Fioletov et al., 2004).

Advanced and comprehensive data assimilation methods are essential to model UV radiation from satellite data. These methods span from directly retrieving surface UV (Li et al., 2000), to statistical models (Fioletov et al., 2001), to the Lambert equivalent reflectivity (LER) method (Krotkov et al., 2001), to inversion algorithms (Wang et al., 2000; Ciren et al., 2003). The simple and efficient method for retrieving surface UV (i.e., DISORT-based model) relies on ground-based measurements as ground-truthing to improve the estimation accuracy. The statistical model developed to extend the record of UV back to the early 1960s estimates UV values (at individual wavelengths and spectrally integrated) from global solar radiation, total ozone, dew point temperature, and snow cover (Fioletov et al., 2001).

With such a similarity between the ground-based measurements and satellite data, a suite of trend analyses in regard to the UV variations at differing scales is feasible. By using datasets from the NASA TOMS from 1979 to 1992, Udelhofen (1999) confirmed that statistically significant increases in erythemal UV radiation exposures have occurred during the summer months in the tropics of the Australian continent over multiple decades. These were associated with a simultaneous depletion of ozone and a decrease in cloud cover. Chubarova (2000) analyzed the UV trend with UV irradiance data from Moscow over a 30-year study period. An algorithm was developed to calculate the variability in erythemally weighted (EW) irradiance for the entire period. The analysis of variability in UV 380 and EW irradiance showed a slight increase in UV values since the middle of the 1980s.

Fioletov et al. (2001) explored variations of the UV-I in the context of climatology using both ground-based measurements and satellite data without including spatial analyses. Herman (2001) studied the phenomena of the quasi-biennial oscillation (QBO), and found that it can cause interannual changes of UV-B exposure by 61.5% at 300 nm and 65% at 310 nm at the equator and at middle latitudes.

As seen from the literature review above, major efforts have been devoted to conduct time series and trend analyses of UV radiation. In this chapter, a thorough comparative analysis is conducted between the daily UV-B doses estimated from the Nimbus-7/TOMS data and those calculated from the ground-based spectroradiometer measurements. Ground measurements of daily UV-B data from 2000 to 2005 were collected around noontime (11:00 ~ 13:00) at the 37 ground monitoring stations in the USDA network. The corresponding TOMS data was investigated for the purpose of comparison. To show the statistical relationship between these datasets, an assessment of UV-I climatology was performed based on four representative ground stations.

10.2 Materials and Methods

10.2.1 USDA UV-B Dataset

The UVMRP provides the USDA with the UV-B-1 radiometer information necessary to determine if changing levels of ultraviolet light have an effect on food and fiber production in the U.S. The primary objective of the UVMRP is to provide information to the agricultural community about the geographic and temporal climatology of UV-B irradiance. All data from the network is captured by on-site data loggers and downloaded over phone lines each morning. Data is made available to the scientific community, as well as the general public, for next day retrieval via the network's World Wide Web site at http://uvb.nrel.colostate.edu. Figure 10.1 shows the locations of all 37 ground stations and highlights 4 sites (circled) selected for a detailed statistical analysis, namely, stations WA01, CA01, CO01, AZ01. These 4 stations are geographically well-distributed, with WA01 located in the north, AZ01 in the south, CO01 in the center, and CA01 in the west.

10.2.2 TOMS Dataset

In contrast to the ground-based point measurements, satellite data may provide us with global coverage at a moderate resolution by standard sensors that have been observing UV from space for more than 20 years. The EP/TOMS dataset can be used for monitoring long-term trends in total column ozone as well as the seasonal

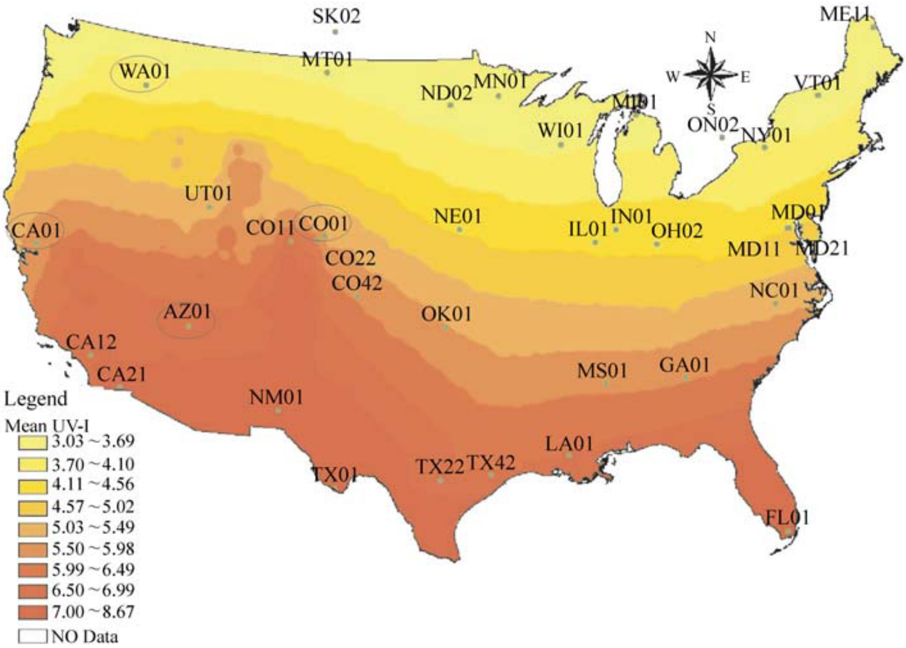


Figure 10.1 Map of the 37 USDA ground stations, 4 of which are circled for statistical analysis

chemical depletions in ozone that occur in both the southern and northern hemisphere polar springs. EP/TOMS also generates the erythemal exposure data product, which is an estimate of the daily integrated UV irradiance, calculated by using a model of the susceptibility of Caucasian skin to sunburn (erythema). This can be interpreted as an index of the potential for biological damage due to solar irradiation, and depends on the column ozone amount and cloud conditions on a given day.

The erythemal exposure was used in this study as a means for UV-B estimation from TOMS satellite data, and is mathematically defined by the following integral,

$$\mathrm{Exp} = \frac{1}{d_{\mathrm{es}}} \int_{280\ \mathrm{nm}}^{400\ \mathrm{nm}} \mathrm{d}_{\lambda} S(\lambda) W(\lambda) \int_{t_{\mathrm{ss}}}^{t_{\mathrm{sr}}} \mathrm{d}_{t} C(\lambda, \vartheta, \tau_{\mathrm{cl}}) F(\lambda, \vartheta, \Omega) \qquad (10.1)$$

where d_{es} is the distance from the earth to the sun (A.U.); S is the solar irradiance incident on the top of the atmosphere at 1 A.U. (nW m^{-2} nm^{-1}); W is the biological action spectrum for erythemal damage (B.D.); t_{sr} and t_{ss} are the time of sunrise and sunset (radian), respectively; C is the cloud attenuation factor (unitless); τ_{cl} is cloud optical thickness (unitless); ϑ is the SZA that is a function of time (radian); F is the spectral irradiance at the surface under clear skies normalized to unit solar spectral irradiance at the top of the atmosphere (unitless); and Ω is the total column ozone (DU).

According to McKinlay et al. (1987), the earth-sun distance, times of sunrise and sunset, and the dependence of the SZA on the time of day depend on the latitude and the time of year, and are calculated from standard formulae. The extraterrestrial solar irradiance incident at the top of the atmosphere when the earth is at a distance of 1 A.U. from the sun was measured over the wavelength interval of interest by the UARS/SOLSTICE instrument. The weighting function used to approximate the wavelength-dependent sensitivity of Caucasian skin to erythema-causing radiation followed the model proposed by McKinlay and Diffey (1998a, b) and was adopted as a standard by the Commission Internationale de l'Éclairage (CIE).

10.2.3 UV Index

The term "erythema" refers to the reddening of the skin due to sunburn. For UV-induced erythema, the action spectrum adopted by most international organizations is the CIE, International Commission on Illumination's action spectrum (E), using the method described by McKinlay and Diffey (1987a, b). The erythemal action spectrum is specified over three spectral ranges as: (1) $W(\lambda) = 1$ for 250 nm $< \lambda <$ 298 nm, (2) $W(\lambda) = 10^{0.094(298 - \lambda)}$ for 298 nm $< \lambda <$ 328 nm, and (3) $W(\lambda) = 10^{0.015(139 - \lambda)}$ for 328 nm $< \lambda <$ 400 nm. The UV-I itself is an irradiance scale computed by multiplying the CIE irradiance in watts m^{-2} by 40. For a fairly wide range of atmospheric conditions, the CIE weighted irradiance changes by approximately 1.2% for a change of 1.0% in the ozone value. Thus the clear sky value at sea level in the tropics would normally be in the range 10 – 12 (250 nm – 300 mWm^{-2}), with 10 being an exceptionally high value for northern mid-latitudes. This scale has been adopted by the WMO and the World Health Organization (WHO), and is in use in a number of other countries (Environment Canada, 2008). Ultraviolet intensity is also described in terms of UV-I ranges running from low values (0 – 2) to medium (3 – 5), high (6 – 7), very high (8 – 10) and extreme (11+). Other irradiance integrals exist which describe other physical and biological effects of UV radiation. However, this one has become the one used most often (Environment Canada, 2008).

10.2.4 Comparative Analysis

Using the 37 USDA point measurements of daily noontime (11:00 AM to 1:00 PM) UV-B time series data from 1999 to 2005, across the continental U.S., the UV-I was generated from an irradiance scale that was computed by multiplying the CIE irradiance in watts m^{-2} by 40 (Environment Canada, 2008). By spatially interpolating daily and monthly UV-I data, the seasonal and yearly UV-I spatial data were produced. At the same time, synchronous TOMS data were acquired for the purpose of comparison. Finally, a comparison of daily UV doses estimated from Nimbus 7/TOMS measurements and ground-based spectroradiometric data was conducted to examine the agreement of these two sources of data statistically. To present the comparison in detail, several analyses of the daily variation, trends, and spatial distribution characteristics of UV-I are discussed.

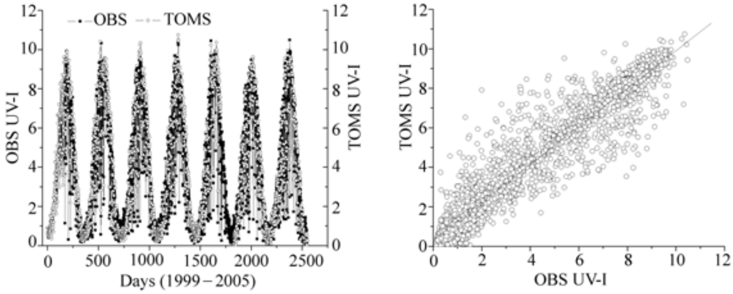
10.3 Results and Discussion

10.3.1 UV-I Daily Change Analysis

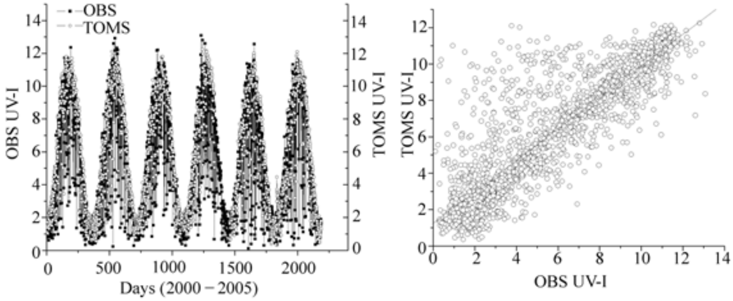
We produced the daily derived UV-I data from 1999 to 2005 that was associated with the four representative ground-based stations and TOMS data to demonstrate the correspondence between the two data sets by statistical analyses (Table 10.1) and to verify the degree of agreement of the data between these two sources (Fig. 10.2). Table 10.1 provides mean, median, minimum, maximum, std. error, standard deviation, values, and correlation coefficients between the datasets. These summary statistics reveal the degree of correspondence between the two data sources. The maxima of the multi-year time series between these two sources are very close, and the absolute disparity is between 0.2 and 0.8 units. Median values from TOMS were always larger than those from USDA ground-based observations. As for the mean values, TOMS data are 5% to 12% larger than those of the USDA ground-based observations. The standard error of mean at these four stations is between 5.9% and 7.6%. Both standard error of mean and standard deviation are very close at three of the stations—WA01, CA01, and CO01, which shows the

Table 10.1 Daily statistical analysis of UV-I data collected from four ground stations and the TOMS data

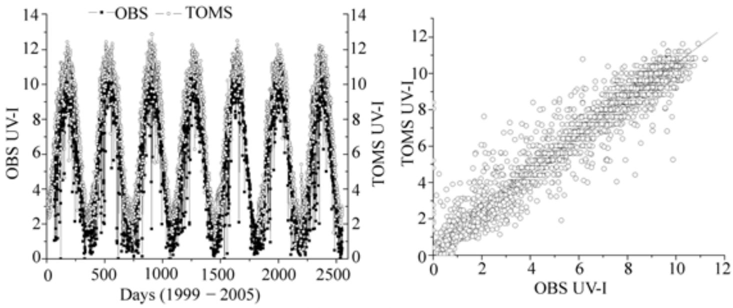
	WA01		CO01		CA01		AZ01	
	USDA	TOMS	USDA	TOMS	USDA	TOMS	USDA	TOMS
Minimum	0.12	0.01	0.11	0.35	0.00	0.03	0.00	0.42
Maximum	10.50	10.70	13.08	12.24	11.20	11.63	14.20	12.86
Mean	3.84	4.03	5.20	5.83	5.26	5.83	6.53	6.95
Median	3.08	3.56	4.44	5.47	5.28	5.97	6.02	7.18
Std. error	0.059	0.060	0.073	0.074	0.063	0.066	0.076	0.067
Std. deviation	2.91	2.96	3.38	3.39	3.13	3.26	3.73	3.28
Correlation coefficient	0.94		0.87		0.96		0.87	



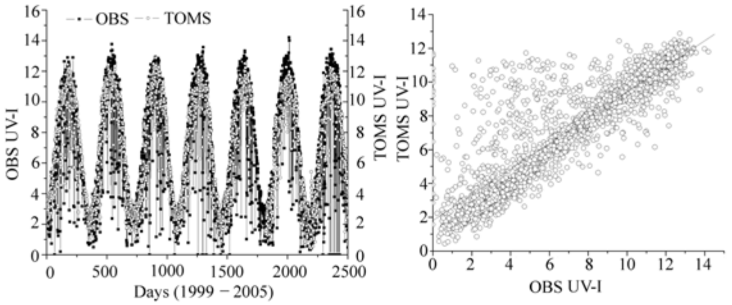
(a) At station WA01



(b) At station CO01



(c) At station CA01

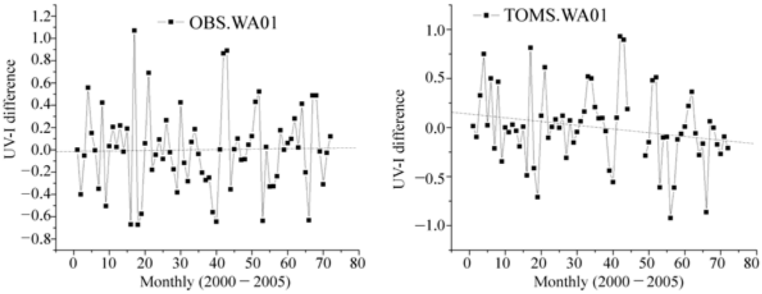


(d) At station AZ01

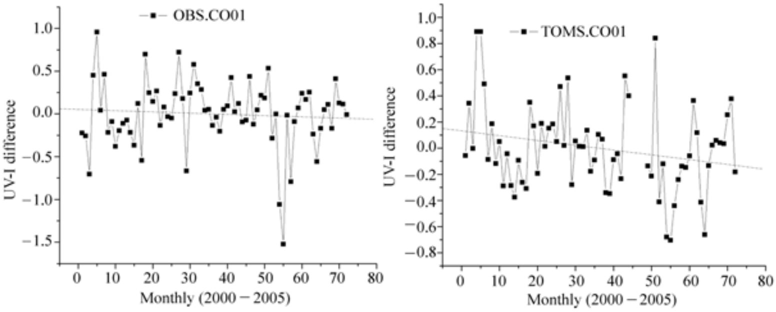
Figure 10.2 Daily UV-I time series variations (left) and the scatter plot along the 45° angle bisector between the TOMS data and the USDA ground-based measurements (right) at 4 stations similarity in fluctuations. The correlation coefficients associated with WA01 and CA01 are higher than 90% (i.e., significant test $P < 0.0001$), whereas the correlation coefficients associated with stations CO01 and station AZ01 are about 87% (i.e., significant test $P < 0.0001$). Such high agreement can also be seen in Fig.10.2, which plots the time-series of UV-I data and also the UV-I values from each data source against each other for all stations. Although there are some outliers that fall out of the 45° angle bisector (i.e., the one-to-one line), these scatter plots highlight the generally good agreement between the two datasets.

10.3.2 Analysis of UV-I Variability

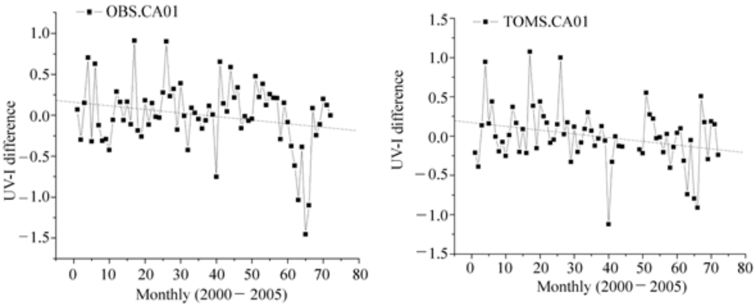
This section compares trends in the data for monthly differences from the mean value over the six-year period. Positive values indicate greater UV exposure than the mean and negative values indicate reduced UV exposure. Comparing such sequences associated with both data sources may enable us to identify the general trend and can also characterize how the patterns they detect differ. Figure 10.3 summarizes such an analysis as a whole using a series of time series plots. Within each plot, the y axis represents the UV-I difference relative to the mean and the x axis represents the month over the study period. On a monthly time scale, UV-I peak values agree between the two datasets. The mean square values of the UV-I deviation from the monthly means at the WA01 station are 9.75 and 9.69 for the TOMS and ground-based measurements, respectively. Obviously, similar fluctuations of these two data sources are confirmed. Yet the negative slope of TOMS time series data at station WA01 indicates a decrease of the deviation relative to the monthly means of the multi-year UV-I time series trend, which is quite different from the long-term trend of the ground-based measurements at this station. At station CA01, the two datasets differ substantially in terms of both the locations of the peak values and the overall trend. The mean square values of the UV-I deviation from the monthly means at station CA01 are 9.43 and 11.39 for the TOMS and ground-based measurements, respectively. The unique finding is that TOMS data show a decreasing trend in the ground-based measurements. At station CO01, the negative slopes of both deviations relative to the monthly means show a decreasing trend associated with both data sources at this station. The mean square values of the UV-I deviation from the monthly means at station CO01 are 7.43 and 10.61, associated with TOMS and ground-based measurements, respectively. As for the analysis at station AZ01, the deviations relative to the monthly means indicate stronger monthly variation in both data sources. The mean square values of the UV-I deviation from the monthly means at station AZ01 are 11.56 and 18.88, associated with TOMS and ground-based measurements, respectively, which are much larger than those for the three other stations. The small positive slope of deviations relative to the monthly means of ground-based measurements shows an increasing trend but the TOMS data appear to be slightly decreasing at this station.



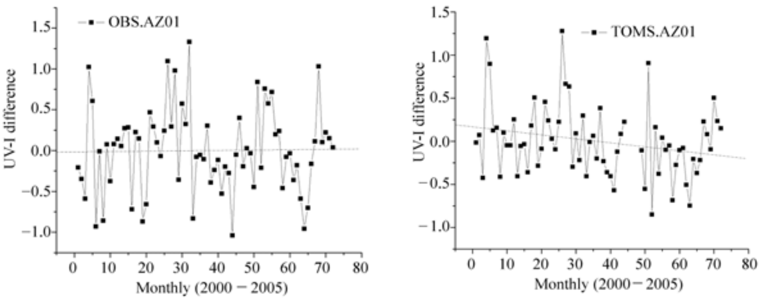
(a) Ground-based measurements at WA01 ;TOMS time series data at WA01



(b) Ground-based measurements at CO01 ;TOMS time series data at CO01



(c) Ground-based measurements at CA01 ;TOMS time series data at CA01



(d) Ground-based measurements at AZ01 ;TOMS time series data at AZ01

Figure 10.3 Trend analysis of the UV-I deviations relative to the monthly means associated with these two data sources at four stations

By comparing the four cases above, it can be concluded that the variability in the TOMS data fluctuations are changing with time at a greater rate than are the fluctuations in the USDA data. Because they are located at high elevation with less impact from clouds, ground-based measurements at stations CO01 (i.e., elevation 1641 m) and AZ01 (i.e., elevation 2073 m) are more consistent with the satellite observations. At the other 2 stations, WA01 (i.e., elevation 804 m) and CA01 (i.e., elevation 18 m), the corresponding impacts from surface clouds and climate factors become obvious. Time series longer than six years might help clarify such discrepancies in the future.

10.3.3 UV-I Spatial Analysis

Spatial patterns of UV-I observed by both data sources were also compared at a 4×4 km spatial resolution. Figures 10.4 − 10.7 collectively delineate the comparison of seasonal UV-I spatial patterns between ground-based measurements and TOMS satellite data. Figure 10.4 first summarizes these spatial patterns of the ground surface UV-I data by season. The two data sources portray very similar spatial distributions of springtime UV-I (Fig. 10.4). The maximum of the UV-I is 9 for the USDA ground-based measurements during spring. The region between the south of New Mexico and Texas and the southern tip of Florida, where the UV-I values exceed 8, accounts for 4.5% of the total study area. However, using the TOMS satellite data, the maximum of the UV-I in spring is 10.3, and the region where the UV-I values exceed 8 accounts for 13.6% of the total study area. This region covers almost all the southern states in the Gulf of Mexico up to the southern Colorado plateau. The minimum UV-I in spring is 3.4. Using the USDA ground-based measurements, the region surrounding the northern states and the Great Lakes, where the UV-I values are less than 4, accounts for 5.4% of the total study area, whereas, using the TOMS data, it accounts for 9.8% of the total study area. Overall, the means of the USDA ground-based measurements and the TOMS data are 5.8 and 6.1, respectively. The lower ground-based measurements could be attributed to the fact that they are interpolated from the point data, and are thus constrained to range between the values observed at the stations. The standard deviations of the UV-I values based on these two data sources are 12.15 and 15.64, respectively. From the minimum and maximum values associated with both data sources, it can be concluded that the TOMS data may exhibit more versatile spatial patterns in response to the terrain complexity. Due to the restrictions of surface observations, the UV-I spatial distribution based on the USDA ground-based measurements, shows less sensitivity in response to topographic features and terrain complexity. This is especially true in the Colorado Plateau.

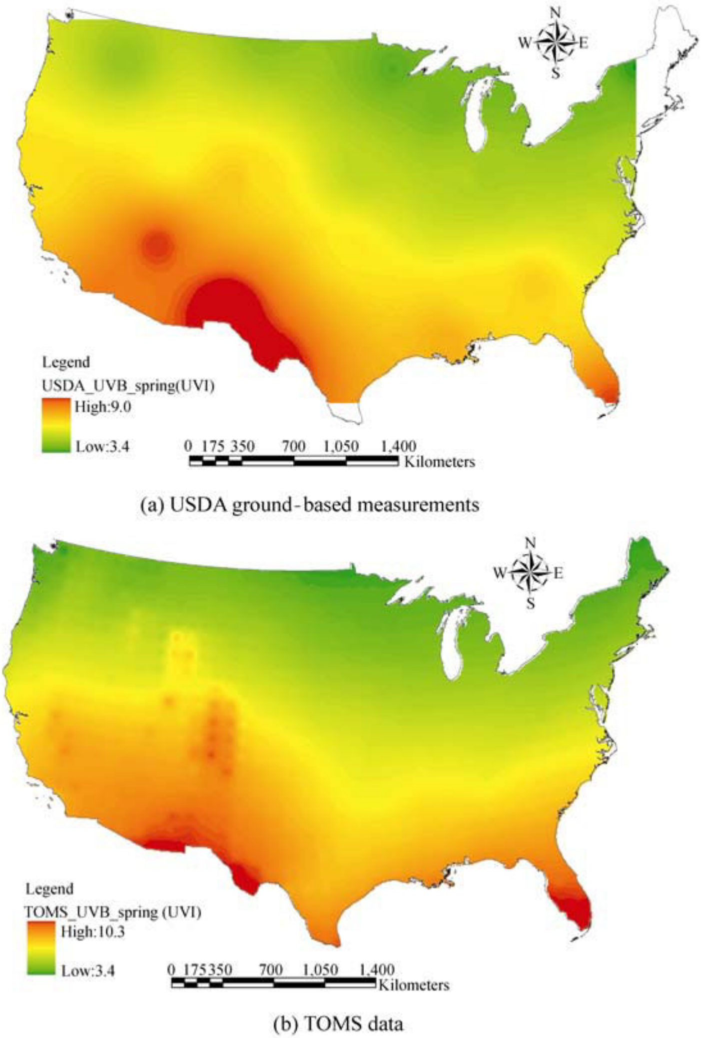


Figure 10.4 Map of the UV-I spatial distributions in spring based on (a) USDA ground-based measurements and (b) TOMS data

In contrast, the UV-I spatial distribution maps associated with the two data sources in summer (see Fig. 10.5) do not portray similar patterns across the continental U.S. In summary, the maximum summertime UV-I is 10.6 with the USDA ground-based measurements. The area where the UV-I values exceed 10 accounts for 3.4% of the total study area. It spreads from the south of New Mexico and Texas, but is absent from the southern tip of Florida. The maximum of the UV-I in summer is 12 with the TOMS satellite data. The area where the UV-I values exceed 10 accounts for 20.9% of the total study area. It spreads from the

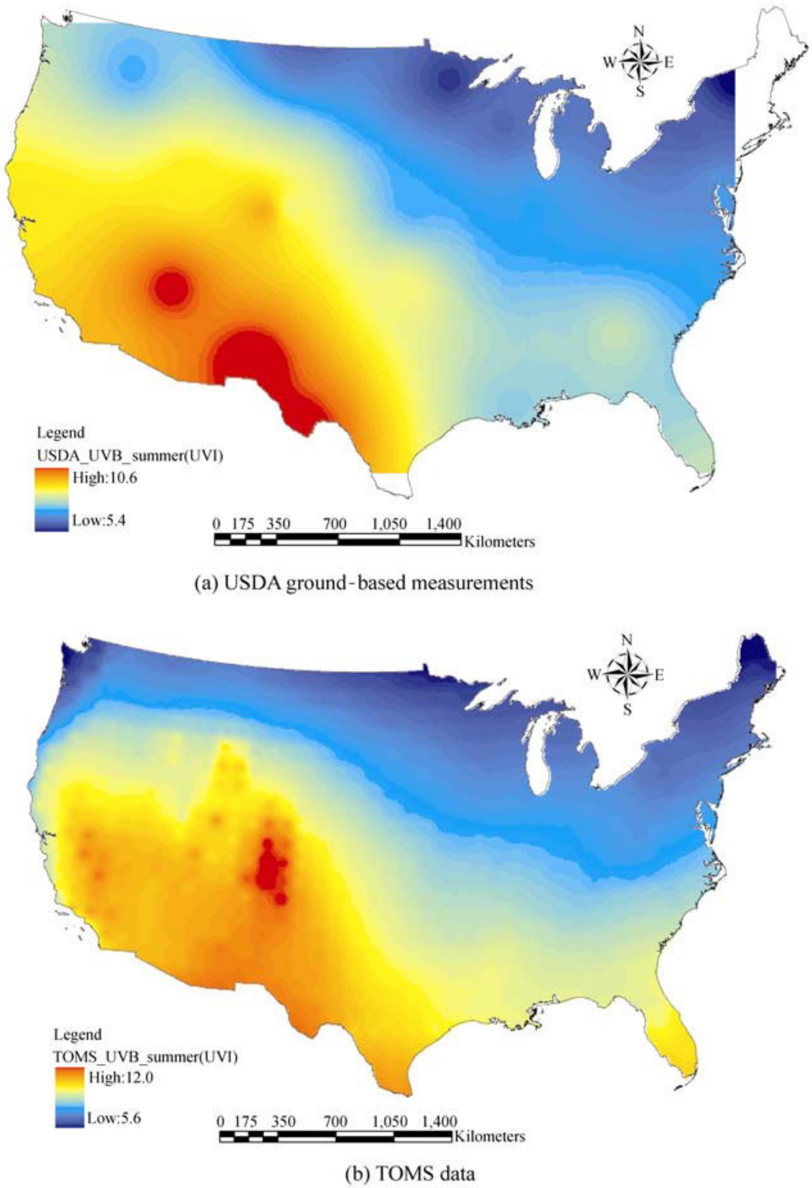


Figure 10.5 Map of the UV-I spatial distributions in summer based on (a) USDA ground-based measurements and (b) TOMS data

Colorado Plateau to southern Texas. The minimum from the USDA ground-based measurements data in summer is 5.4 and the area where the UV-I values are less than 6 accounts for 2.7% of the total study area. On the other hand, the minimum of TOMS satellite data in summer is 5.6 and the area where the UV-I values are less than 6, located mostly in the northern part of Wisconsin, Michigan, and Maine, accounts for 0.7% of the total study area. Overall, the means of the USDA ground-based measurements and the TOMS data are 7.8 and 8.6, respectively. The standard deviations of the UV-I values based on these two data sources are 11.42 and 13.75, respectively. As in the spring, it can be concluded from the range of values associated with both datasets that the summertime TOMS data may exhibit more versatile spatial patterns in response to the terrain complexity.

The UV-I spatial distribution maps for fall (see Fig. 10.6) portray very similar patterns across the continental U.S. for both data sources (i.e., USDA and TOMS).

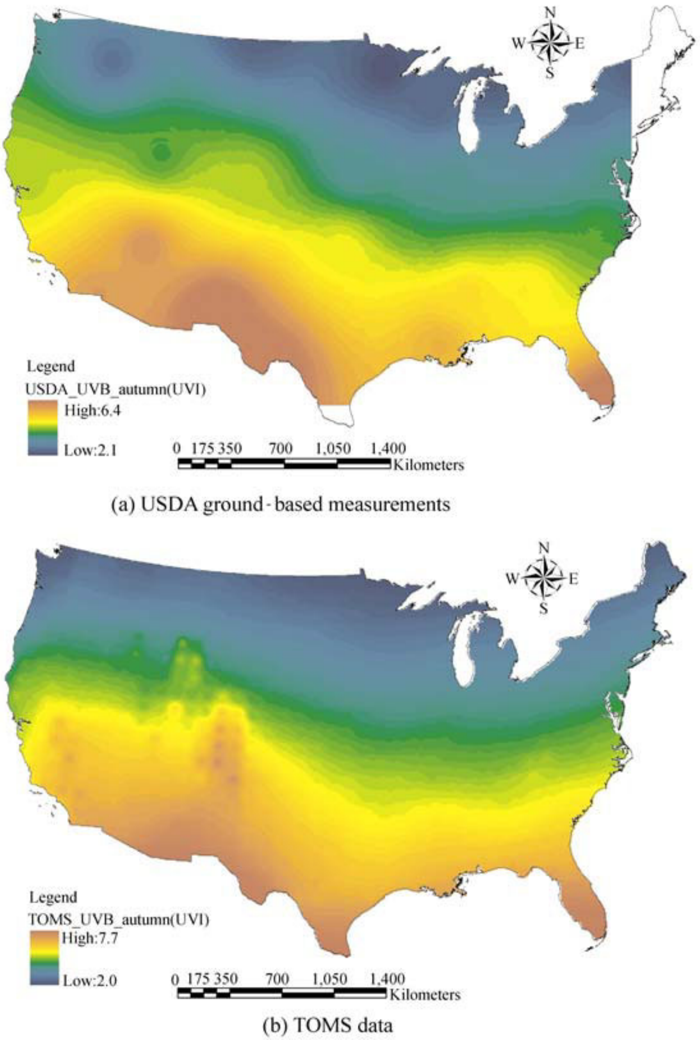


Figure 10.6 Map of the UV-I spatial distributions in fall based on (a) USDA ground-based measurements and (b) TOMS data

In summary, based on the USDA ground-based measurements, the maximum of the UV-I in fall is 6.4. The region spreading from the south of New Mexico, where the UV-I values exceed 6, accounts for 0.8% of the total study area. The maximum of the UV-I in fall is 7.7 based on the TOMS satellite data. The region covering southern Arizona, New Mexico, Texas and Florida, where the UV-I values exceed 6, accounts for 10.1% of the total study area. The minimum of the fall USDA ground-based measurements data is 2.1, and the area where the UV-I values are less than 2.0 accounts for 22.5% of the total study area. On the other hand, the minimum of TOMS satellite data in fall is 2.0, and the area where the UV-I values are less than 2.0 accounts for 18.7% of the total study area, located mostly in the northern part of the continental U.S. Overall, the means of the USDA ground-based measurements and the TOMS data are 3.8 and 4.3, respectively. The standard deviations of the UV-I values, based on these two data sources, are 9.25 and 12.43, respectively. Again, the TOMS data appear to be more sensitive to spatial patterns in response to the terrain complexity.

The two UV-I spatial distribution maps in winter (see Fig. 10.7) are also very similar. In summary, based on the USDA ground-based measurements, the maximum of the UV-I in winter is 4.8. The region located in the south of Texas and Florida, where the UV-I values exceed 4, accounts for 0.6% of the total study area. The maximum of the UV-I in winter is 5.9 with the TOMS satellite data. The region spreading across Arizona, New Mexico, Texas and also southern Florida, where the UV-I values exceed 4, accounts for 2.9% of the total study area. The minimum of USDA ground-based measurements data in winter is 0.9 and the region spreading from Minnesota and Michigan, to New York, where the UV-I values are less than 1.0, accounts for 2.7% of the total study area. On the other hand, the minimum of TOMS satellite data in winter is 0.3 and the region mostly located in the northern part of the continental U.S., where the UV-I values are less than 1.0, accounts for 22.5% of the total study area. Overall, the means of the USDA ground-based measurements and the TOMS data are 2.0 and 2.04, respectively. The standard deviations of the UV-I values based on these two data sources are 6.69 and 10.55, respectively. As with the rest of the year, TOMS data are better able to capture spatial variation in UV-I in response to topography.

Across all seasons, and for both USDA ground-based measurements and TOMS data, the distribution of the UV-I appears to be strongly tied to latitude and topography simultaneously. The higher the latitude, the smaller the UV-I value (Fig. 10.8). The maxima of seasonal and yearly UV-I values are distributed along the latitudes of Arizona, New Mexico, Texas, and southern Florida whereas the minima of the values are distributed across the upper latitudes of the Great Lakes and the Central Plains regions. The UV-I values were also greatly influenced by the topography from east to west. Along the same latitude, the UV-I value in the east is normally smaller due to lower altitudes, while the west is larger due to

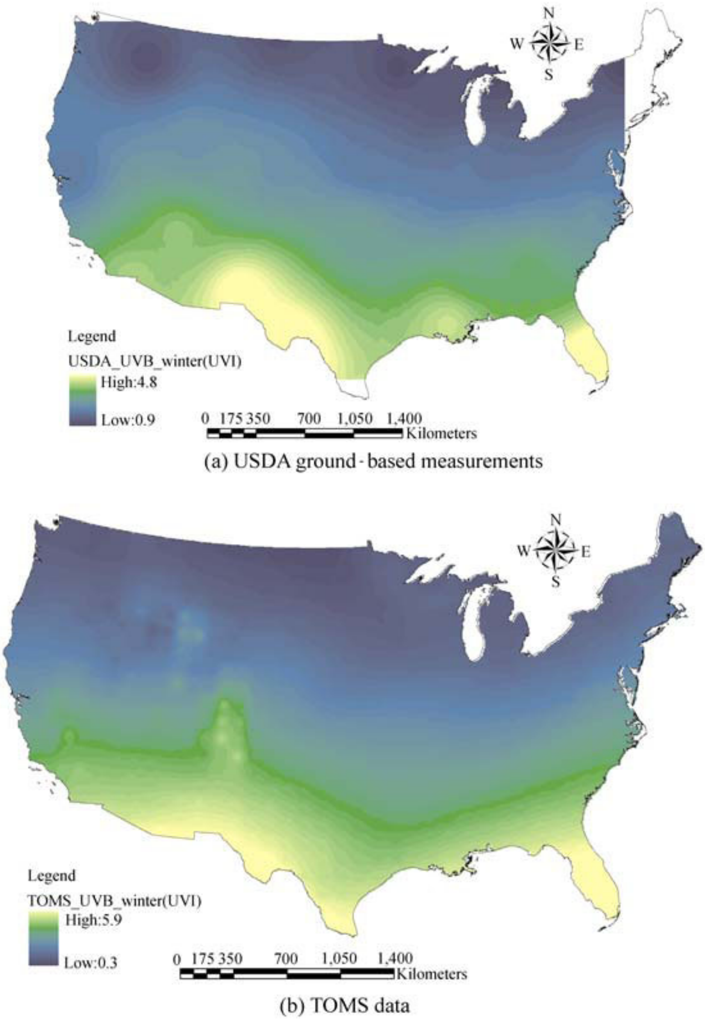


Figure 10.7 Map of the UV-I spatial distributions in winter based on (a) USDA ground-based measurements and (b) TOMS data

higher altitudes. Overall, as a result of the combination of the effects of both latitude and altitude, the UV-I distribution pattern shows a characteristic trend of high values in the southwest and low values in the northeast.

On average, the UV-I values based on TOMS data are 1 – 2 units larger than those based on USDA ground-based measurements. The spatial variation of TOMS data is much more evident and is less generalized than the ground-based counterpart. TOMS data can respond to the topography and latitude remarkably and can easily embody the spatial distribution patterns and characteristics of UV-I. Both types of data accurately depict the macroscopic spatial distribution pattern of UV-I in the continental U.S., but TOMS better captures the coverage of spatial patterns. In any circumstance, the spatial comparisons described above are not intended to be indicative of the overall accuracy of either dataset.

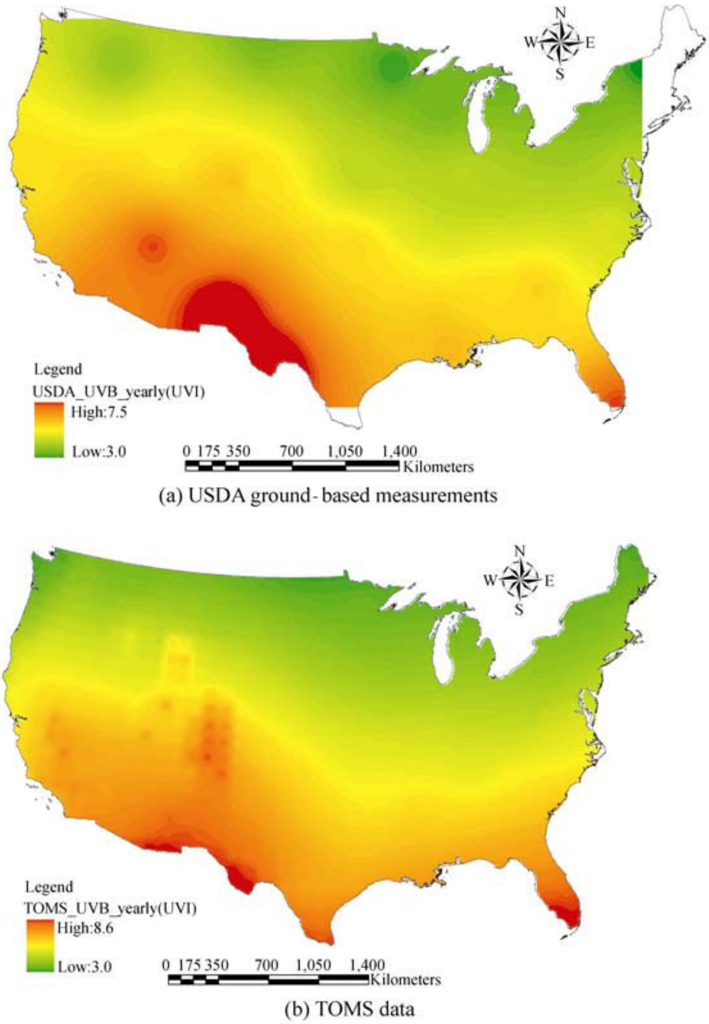


Figure 10.8 Maps of UV-I spatial distributions based on a multi-year average

10.4 Conclusions

This study compares the noontime UV-B data collected by the broadband UV-B-1 Pyranometer measurements against synchronous TOMS data measured over 1999 to 2005 across the continental U.S. These analyses were performed in order to provide insights into how the spatial and temporal patterns of UV-B may be collectively used to identify the UV impacts. For the temporal analysis, we compare trends in the data for monthly differences from the mean value over the five-year period. For the spatial analysis, each TOMS data set is interpolated across the continental U.S. to identify regions with low to high UV exposure for each of the four seasons and across years. However, after describing the patterns of variation in UV exposure across time and space using two continental scale datasets on UV radiation, we conclude that the two approaches are comparable and that the value of each is distinct.

To summarize the trend of daily and monthly changes of UV-I, four specific stations within the USDA network—WA01, CA01, CO01 and AZ01—were chosen for demonstration and comparison. This comparative analysis of UV-I time series data confirmed agreement between the USDA ground-based measurements and the TOMS satellite imageries with correlation coefficients of 0.87 (daily) and 0.95 (monthly). Spatial correlation coefficients between these data sources were as high as 0.93. These observations reveal that both sensors are consistent, reflecting their essential reliability for sensing, modeling, and predictions. Yet the UV-I values observed by the TOMS sensor are generally greater than those of the USDA ground-based measurements by $1-2$ units, on average, with a relative error of daily change between 5% and 12%. In addition, the TOMS data may be better able to represent the essential fluctuations due to latitudinal and topographical features as compared to the USDA ground-based measurements. Although both of these data sources can address the general spatial distribution of the UV-I across the continental U.S., TOMS data can perform relatively better, allowing the more accurate detection of the UV-I distribution pattern that uniquely delineates a transitional change from the high southwest and low northeast UV readings.

Such differences between the two data sources in terms of both spatial and temporal characteristics are mainly due to the fact that the TOMS data are satellite-based and remotely sensed with a resolution of 1×1.25 degree, which receive less impact from cloud cover, rainfall, humidity, ozone, and aerosols in the air. Ultraviolet-B radiation is normally reflected, scattered, and absorbed before reaching the land surface. As a consequence, the USDA ground-based measurement could be significantly affected by climatic factors such as cloud cover, rainfall, and temperature, as well as aerosols, ozone, and numerous other factors. Such findings account for the fact that USDA ground-based measurements are often lower than those of the TOMS data. Nevertheless, the USDA ground-based measurements may be better applied for time series analysis due to the capability to conduct intensive point measurements. The TOMS UV-I data that are often about $1-2$ units larger than the USDA ground-based measurements may be more applicable for exploring the regional patterns of UV-I distribution due to higher spatial resolution and sensitivity to the topography.

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